CONCRETE SWELLING IN TWO SPANISH DAMS

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Summary

Several chemical reactions are able to produce swelling of concrete for decades after its initial curing, a problem that affects a considerable number of concrete dams around the world. Principia has had several contracts to study this problem in recent years, which have required reviewing the state-of-the-art, adopting appropriate mathematical descriptions, programming them into user routines in Abaqus, determining model parameters on the basis of some parts of the dams' monitored histories, ensuring reliability using some other parts, and finally predicting the future evolution of the dams and their safety margins.

The paper describes some of the above experience, including the programming of sophisticated non-isotropic swelling models, that must be compatible with cracking and other nonlinearities involved in concrete behaviour. The applications concentrate on two specific cases, an arch-gravity dam and a double-curvature arch dam, both with a long history of concrete swelling and which, interestingly, entailed different degrees of success in the modelling efforts.

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1. Introduction

There are a number of chemical reactions that may cause delayed swelling in concrete. The reactions generally involve the aggregate, the cement matrix and water. The process is very slow, as it typically arises from more than one reaction, with the second one feeding on the results of the first one. Also, water must be available, which migrates only slowly in a concrete mass. In any case concrete swelling, whenever it takes place, entails deterioration and potentially catastrophic consequences for the structure concerned.

Many structures have been and are known to suffer from this problem. In particular it affects a considerable number of concrete dams built towards the middle of the 20th century in many places of the world. The two applications discussed in the present paper are an arch-gravity dam and a double-curvature arch dam dating from that period.

Because of its widespread occurrence and its potential consequences, the phenomenon has been extensively studied by various research institutions or bodies like the International Commission for Large Dams (ICOLD), the American Concrete Institute (ACI), etc. A review of the state-of-the-art is outside the scope of the present paper, but an interested reader may wish to peruse the proceedings of the International Conferences on Alkali-Aggregate Reaction in Concrete, of which the 13th and more recent one was held in 2008 in Trondheim, Norway [1].

Various types of remedial measures have been attempted in the past, ranging from a scientifically questionable treatment of the structure with lithium to the vertical slicing of the dam to relieve the compressive stresses caused by concrete swelling. It seems clear though that the proposal of useful strategies must rely on a sound understanding of the process and an ability to model it reliably, so that predictions can be made about the future of the structure and the likely effects of introducing some mitigating measures.

Based on the results of past investigations, it can be concluded that the factors that have a major influence in the process are the following:

- Material components. Reactive aggregates and alkali-rich cements are needed; additives may also influence the process.
- Time. The formation of a hydrophilic gel is not instantaneous, it involves a latency time; also, once formed, its swelling via an alkali-aggregate reaction (AAR) involves a characteristic time.
- Environmental conditions. As is the case in most chemical reactions, temperature accelerates the process. And, since swelling occurs by absorbing water, moisture conditions play a significant role as well.
- Stress state. High compressive or tensile stresses may affect swelling because of their effects on water pathways, e.g.: by closing cracks or creating spaces for the expanded gel.

The significance of other factors can be considered smaller in comparison.

2. Expansion Models

Following an extensive literature review, the more promising mathematical formulation of the problem appears to be the one proposed by Ulm et al [2], subsequently modified and extended by Saouma and Perotti [3]. Both theories will be described briefly below.

2.1. Model by Ulm et al.

The model by Ulm et al. assumes that the reaction develops following an equation of the type:

$$1-\xi = t_c(\xi,\theta)\frac{\mathrm{d}\xi}{\mathrm{d}t} \tag{1}$$

where ξ is the extent of the reaction, t_c is the characteristic time of the reaction, θ is the absolute temperature, and *t* is the time elapsed. The characteristic time decreases as the reaction progresses:

$$t_c(\xi,\theta) = \tau_c(\theta)\lambda(\xi,\theta) \tag{2}$$

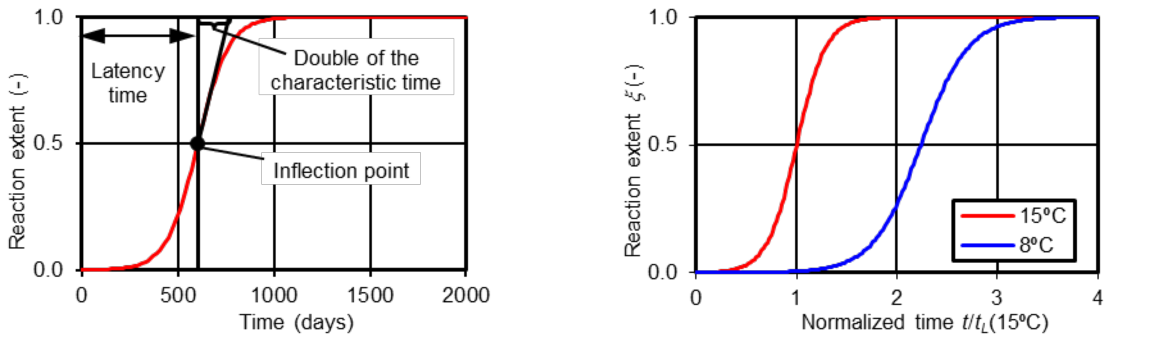
$$\lambda(\xi,\theta) = \frac{1+\exp(-\tau_L(\theta)/\tau_c(\theta))}{\xi+\exp(-\tau_L(\theta)/\tau_c(\theta))} \tag{3}$$

where τ_c is a characteristic time constant.

The latency and characteristic times are both a function of temperature, following the Arrhenius law that governs thermally activated processes. It may be noticed that the above differential equation can be solved analytically in the isothermal case. The parameters involved in the model, with the values proposed by *Larive* [4], are listed below:

- unidirectional expansion at infinite time: 0 to 0.004
- activation energy of the characteristic time: 5400 ± 500 K
- activation energy of the latency time: 9400 ±500 K

The activation energies are already divided by the Boltzmann constant, thus their K units. Figure 1a shows the physical meaning of the two time constants involved. The latency time is the time elapsed to the point of inflection of the curve that depicts the development of the reaction; it is near, but slightly differs from, the time when 50% of the reaction has taken place. The characteristic time is half of the incremental intercept produced by a tangent drawn at the inflection point. Figure 1b shows the effect of temperature in the progress of the reaction.



a) Reaction extent at constant temperature b) Effect of temperature

Figure 1: Reaction extent according to Ulm et al

2.2 Model by Saouma and Perotti

The model by Saouma and Perotti [3] was initially developed to represent the progress of the AAR and its temperature dependence is taken from the model by Ulm et al. They propose that the effects of the volumetric reaction in one space direction will be affected by the others, that the preferred directions for expansion will be the least compressed ones, and that high normal stresses will influence the reaction through mechanisms such as providing space for gel expansion, sealing or opening pathways for water migration, etc.

The effects of the stress level are reflected through its influence on the latency time:

$$\tau_L(\theta,\overline{\sigma}) = f(\overline{\sigma})\tau_L^{\mathrm{ULM}}(\theta) \tag{4}$$

$$f(\bar{\sigma}) = \begin{cases} 1 & \text{if } \bar{\sigma} \le 0 \\ 1+\alpha\bar{\sigma} & \text{if } \bar{\sigma} > 0 \end{cases} \tag{5}$$

where $\bar{\sigma} = -(\sigma_I + \sigma_{II} + \sigma_{III})/(3f_c)$ is the normalized pressure, α is an empirical coefficient, for which Saouma and Perotti propose using 4/3 based on the tests by Multon and Toutlemonde [5], f_c is the compressive strength, and τ_L^{ULM} is the latency time from Ulm et al.

For the evolution of swelling the following equation is proposed:

$$\frac{\mathrm{d}\varepsilon_{\mathrm{vol}}}{\mathrm{d}t} = \Gamma_t(u_{\mathrm{ck}})\Gamma_c(\bar{\sigma})\xi(t,\theta)\varepsilon_{\mathrm{vol}}^{\infty} \tag{6}$$

where Γ_t accounts for the reduction of swelling caused by cracking with crack opening u_{ck}, Γ_c accounts for the reduction of swelling by compression with a normalized pressure $\bar{\sigma}$, and $\varepsilon_{\mathrm{vol}}^{\infty}$ is the free expansion at infinite time.

The dependence on tensile cracking is incorporated by:

$$\Gamma_t(u_{\mathrm{ck}}) = \begin{cases} 1 & \text{if } u_{\mathrm{ck}} \le \gamma_t w_c \\ \Gamma_r + (1-\Gamma_r)\dfrac{\gamma_t w_c}{u_{\mathrm{ck}}} & \text{if } u_{\mathrm{ck}} > \gamma_t w_c \end{cases} \tag{7}$$

where γ_t governs the reduction of expansion in tension, Γ_r is the coefficient of residual expansion in tension, w_c is the maximum crack opening in the tensile softening curve. The effect of compression is introduced as:

$$\Gamma_c(\bar{\sigma}) = \begin{cases} 1 & \text{if } \bar{\sigma} \le 0 \\ 1-\dfrac{e^{\beta}\bar{\sigma}}{1+(e^{\beta}-1)\bar{\sigma}} & \text{if } \bar{\sigma} > 0 \end{cases} \tag{8}$$

where β is an dimensionless parameter.

Apart from determining the volumetric expansion, the model must also distribute it among the three space directions. For example, in uniaxial tension, the amount of chemical swelling would be identical in all directions; but in uniaxial compression, with the stress above a certain threshold σ_u, the chemical expansion would only occur in the two transverse directions. Figure 2 shows how the model distributes the expansion in the various stress states.

3. Numerical implementation

The model by Saouma and Perotti described in the previous section was implemented in Abaqus/Standard [6]. For this purpose a user subroutine was created to determine incrementally the imposed deformations caused by both the expansive chemical reaction and thermal dilation. Such increments are a function of temperature, progress of the reaction, pressure, and crack opening.

The calculation requires information about the principal stresses and directions and must be combined with the plasticity and the continuous damage model of the concrete. State and field variables are updated in another user subroutine and moisture is introduced as an independent field variable. The rest of the variables are updated at the beginning of each time step, thus in an explicit scheme, but are extrapolated to mid-step from their most recent values. The size of the time step may therefore play an important role and the sensitivity to this parameter should be studied for each specific application. For cases such as discussed in the present paper, experience indicates that generally 2 weeks is an adequate time step. Other subroutines were also written to impose yearly periodic boundary conditions for thermal analyses and to vary the hydrostatic pressure.

Many analyses were carried out on a single element of 25 MPa concrete to ascertain that the model was working as intended. Figure 3a shows the progress of the reaction at 15ºC for various stress conditions, slowing down as pressure increases; apart from the rate of progress, the final volumetric expansion is also affected by pressure, as can be seen in Figure 3b.

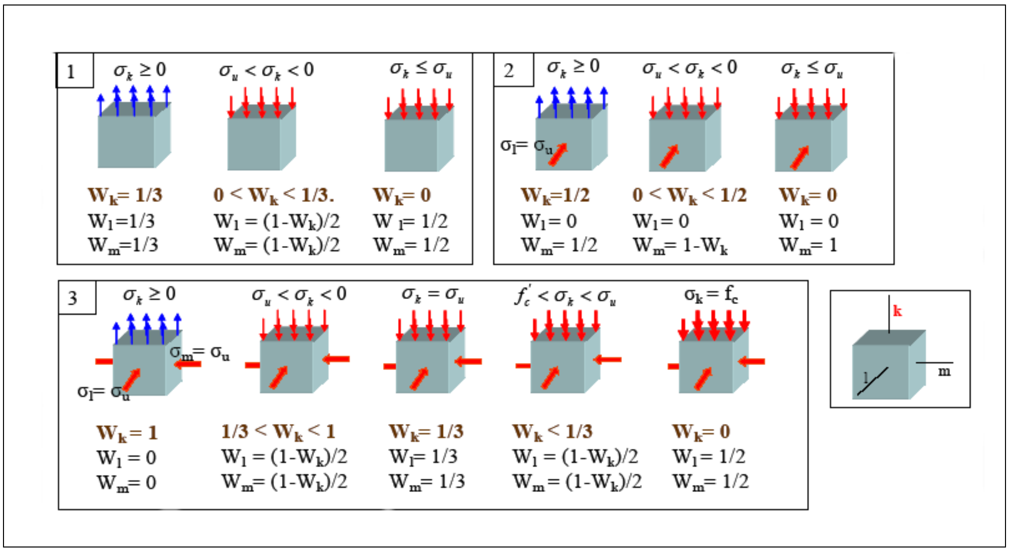
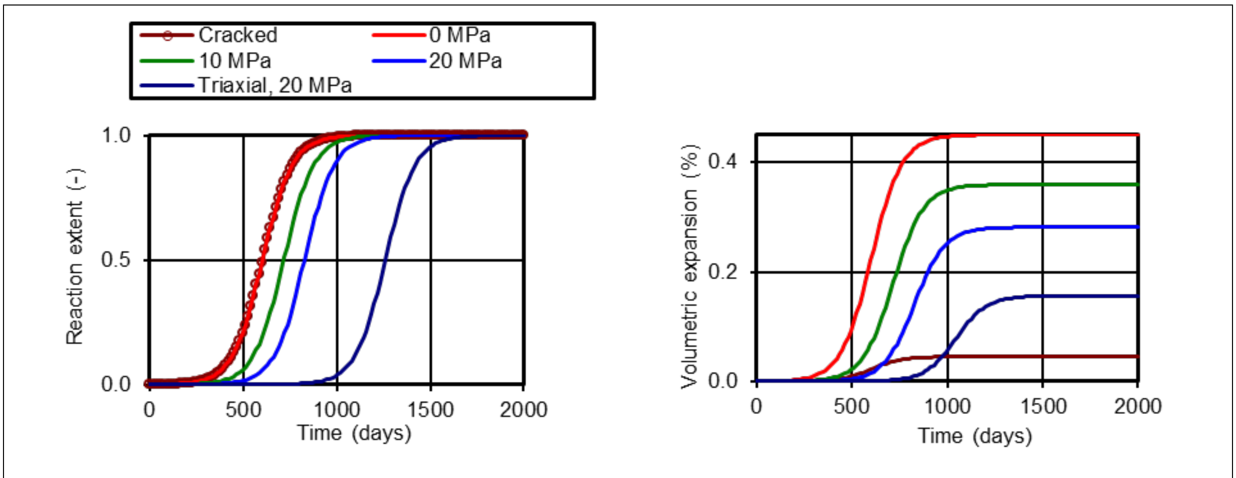


Figure 2: Distribution of expansion after Saouma and Perotti



a) Reaction extent

b) Volumetric expansion

Figure 3: Reaction extent and volumetric expansion by Saouma and Perotti

The distribution of expansion between the various directions is shown in Figure 4, which corresponds to different stress conditions and 37ºC, a temperature that is typical of the accelerated swelling tests conducted in the laboratory. The latter figure confirms that, even under considerable compression in all directions, swelling decreases but does not vanish.

4. Application to an arch-gravity dam

Figure 5 shows the dam, including the plan view the cross-section. It is an arch-gravity dam, built in 1955, with a height of 115 m and a radius of curvature of 120 m. The dam was known to be suffering from concrete swelling from a relatively early stage. Although the extrapolation of the ongoing phenomena did not give reasons for serious concern, the state-of-the-art did not allow providing satisfactory descriptions of the process and reliable models of its likely evolution.

4.1. Available data and methodology

In this reservoir water levels change very little throughout the year and the hydrostatic load on the dam is therefore reasonably constant. Air and water temperatures have been carefully recorded throughout the history of the dam. Detailed information is also available about displacements at a dense array of points of the dam; unfortunately there is very scant information about temperatures in the concrete, which is a key parameter in the expansion process.

For lack of better information, the concrete of the dam was considered homogeneous, though there were some indications that this might not be the case. The basic mechanical parameters used were Young's modulus 21 GPa, Poisson's ratio 0.17, compressive strength 31 MPa, tensile strength 2.5 MPa, and density 2300 kg/m^3; and from the thermal viewpoint they were thermal conductivity 1.75 W/mK, specific heat 800 J/kgK, and thermal expansion coefficient 10^{-5} K^{-1}.

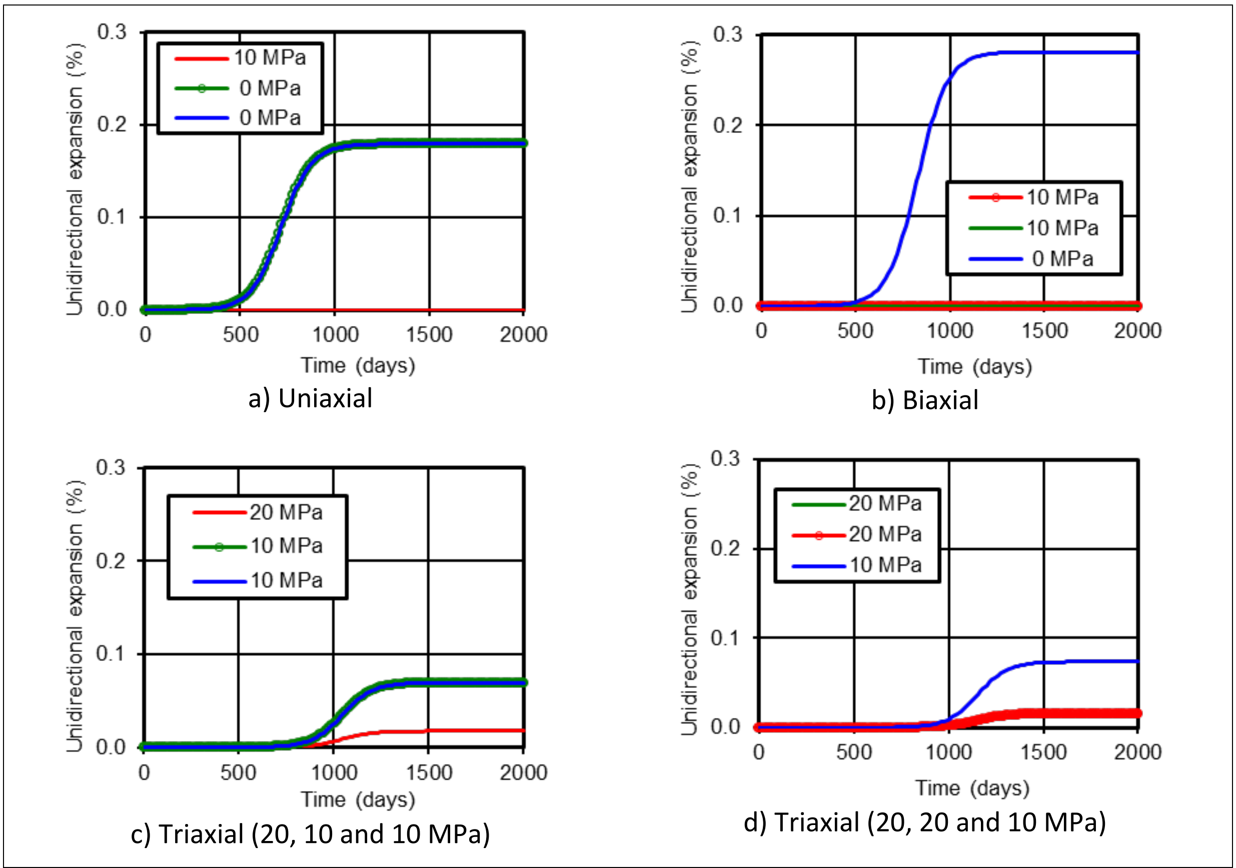


Figure 4: Unidirectional expansion

The dam had been constructed in 17 independent blocks. Friction between neighbouring blocks was assumed to be governed by a Coulomb friction coefficient of 0.5.

To study the evolution of the swelling process, an average thermal year was first produced; the evolution of the dam would then be studied under successive yearly cycles. This was done by averaging the measurements and fitting the data with Fourier series. The heat conduction equation was then solved, starting from an assumed initial temperature of 14ºC and using the known air and water temperatures; the thermal analysis proceeded until a cyclic steady-state appeared in the concrete. The analysis produced the temperature evolution at all points in the dam.

The contact of the dam with its foundation was assumed rigid in the normal direction, while relative displacements in the tangential direction were controlled by a subgrade reaction modulus.

The strategy followed was to calibrate the parameters of the swelling model to achieve an optimal reproduction of the radial displacements at block 3i of the dam, hoping that this would also result in reasonable approximations for the displacements in other directions and locations.

4.2. Results obtained

The yearly evolution of air and water temperatures is shown in Figure 6. The mesh used to analyse the dam appears in Figure 7; the thermal analyses are based on linear tetrahedrons, while the structural calculations employ second order elements.

For the expansion model, the activation energies of the latency and characteristic times were assigned the central values proposed by Larive [4]. The other parameters of the expansion model were fitted in order to match the radial displacement trend at block 3i of the dam, a fit that can be seen in Figure 8.The values obtained were:

- expansion at infinite time: 0.0015
- latency time: 10,000 days
- characteristic time: 2,500 days

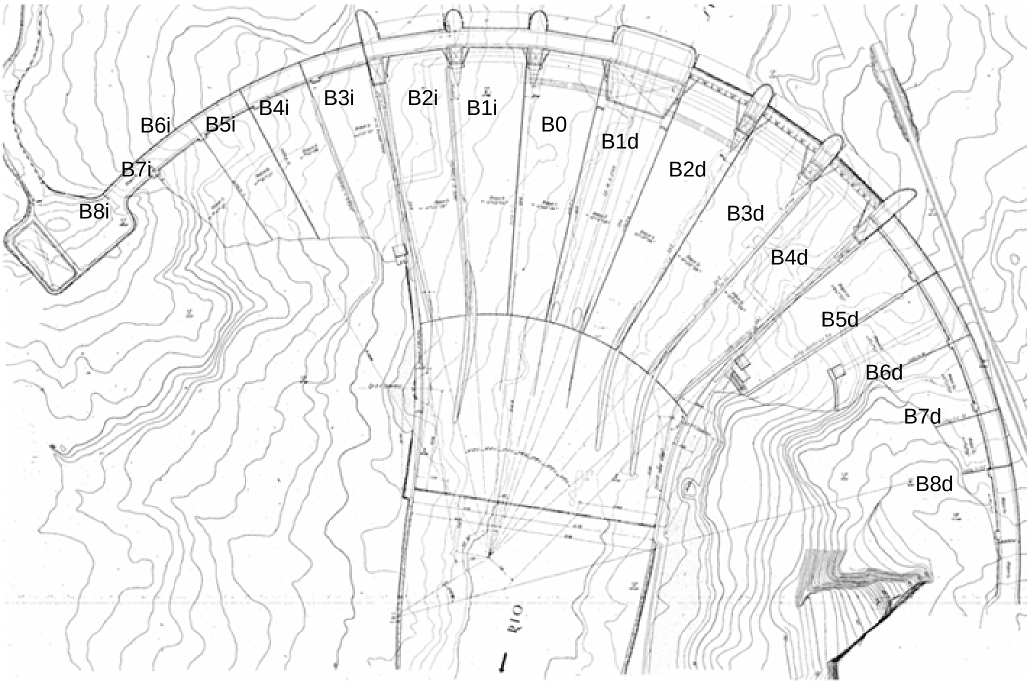
Moisture inside the dam was assumed to vary linearly across its thickness. Another uncertain parameter was the effect of the greater solar exposure of the region near the right abutment of the dam, which is difficult to incorporate precisely because of the lack of temperature records in the concrete. The influence of these two parameters was combined into a single field variable.

Starting from the end of construction, the evolution predicted by the calibrated expansion model leads to the distributions of radial and vertical displacements shown in Figure 9. When compared with the actual measurements, these displacements can be termed reasonable, but not fully satisfactory. This is evinced by Figure 10, which shows a comparison of the calculated and recorded displacement trends at three different blocks of the dam. The orders of magnitude are correct in all cases and the displacements at block 3i, used for the calibration, obviously produce a good match; however, the displacements at block 0, and particularly at block 3d, are not reproduced with the same quality.

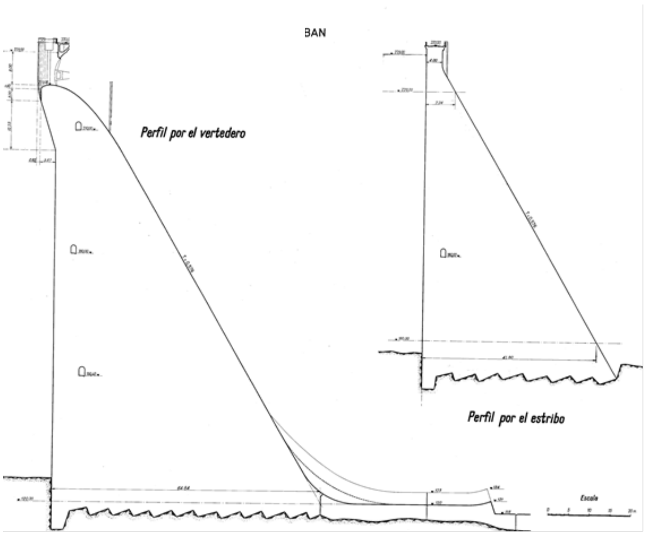
Many attempts were made to lessen this discrepancy, most of which were eventually ruled out, like motions of the ground slopes or enhanced effects of moisture or temperature. Temperature records in the concrete would have certainly helped to decrease uncertainties, but it was finally concluded that the observed distribution of displacements required some degree of heterogeneity in the concrete.

5. Application to a double-curvature arch dam

The dam is a 132 m dam built roughly 50 years ago. Swelling phenomena were recognised from a relatively early stage and continue today. A general view of the dam is provided in Figure 11. The early identification of the problem caused the installation of additional instrumentation, thereby producing a wealth of detailed monitoring data that would not exist otherwise.



a) Plan view.



b) Sections

Figure 5: Drawings of the arch gravity dam

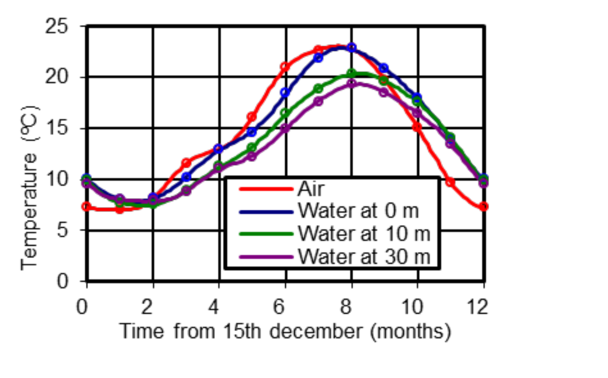


Figure 6: Temperatures in air and water

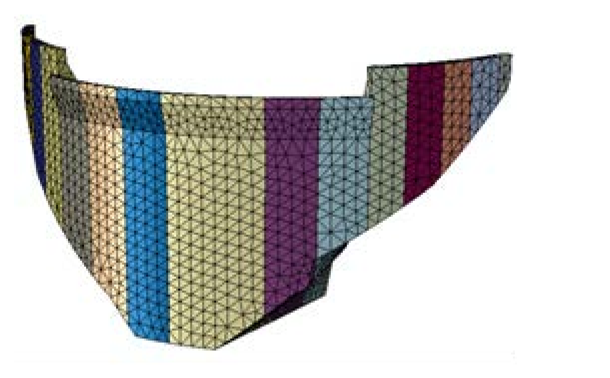


Figure 7: Mesh of the arch gravity dam

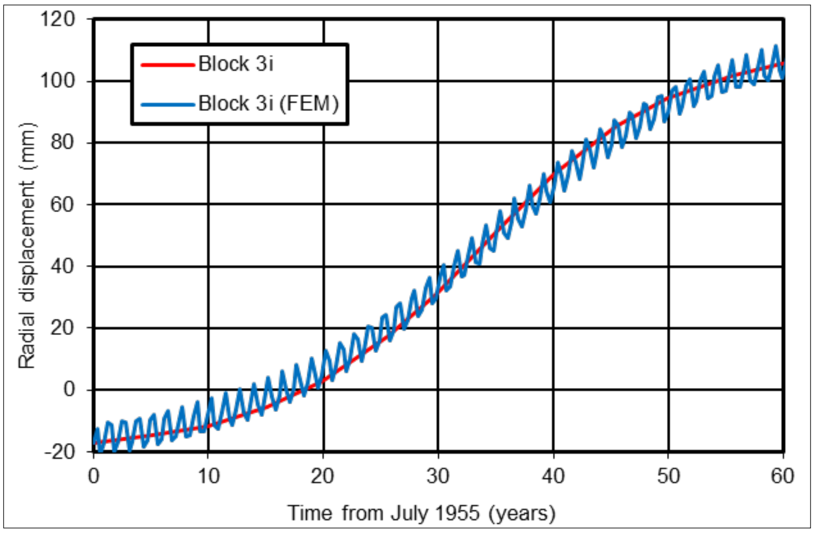
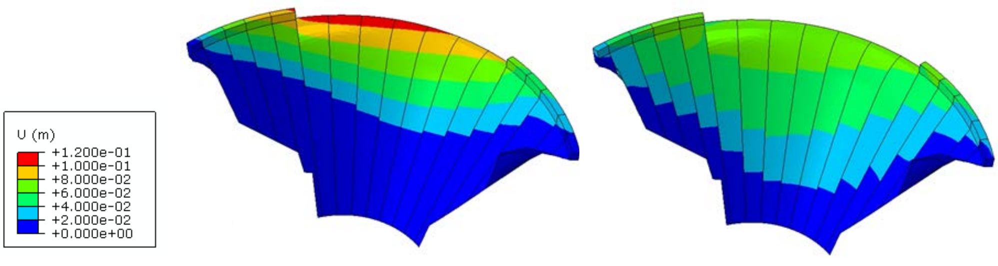


Figure 8: Adjustment of movements in block 3i



a) Radial b) Vertical

Figure 9: Displacements in July 2010 (m)

5.1. Available data and methodology

The dam has several thousand channels of instrumentation, many of which have been producing data for almost 50 years. For the present purposes, some of them are especially significant:

- records of the demands imposed and the prevailing environmental conditions, such as air and water temperatures at various depths, as well as elevations of the water surface in the reservoir.

- records of the response of the dam, such as temperatures, displacements and other variables at many locations within the body of the dam.

The parameters used for describing the mechanical and thermal behaviour of the concrete concrete were Young's modulus 30 GPa, Poisson's ratio 0.22, compressive strength 30 MPa, tensile strength 3 MPa, density 2300 kg/m^3, thermal conductivity 1.7 W/mK, and specific heat 750 J/kgK. The coefficient of thermal expansion, initially believed to be 1.0 x 10^{-5} K^{-1}, had to be increased later, based on the monitored data, to 1.5 x 10^{-5} K^{-1}.

The data were first used to obtain average years for the evolutions of temperatures at specific locations and of the water surface in the reservoir. The heat conduction equation was then solved, based on the temperatures at some points, to obtain complete temperature histories at all points in the dam, using temperature records at other points for verification.

Having done this, the parameters of the swelling model were calibrated using the displacement records of a one single point at the top of the dam. With these parameters one can then trace the history of the dam, calculating the displacements at all points; this allows verifying the model with other measurements not used in the calibration. Unlike the previous example, it will be seen that the model reproduces well the evolution of the deformations at all points of the dam.

5.2. Results obtained

A representative yearly evolution of the water levels in the reservoir was determined averaging and fitting with Fourier series. For the thermal analyses, Figure 12a shows the mesh used, made of about 90,000 linear tetrahedral elements. The thermal analysis is marched forward sufficiently to remove the influence of the unknown initial conditions; the resulting distribution of temperatures in the dam appears in Figure 13. Because of its more southernly orientation, the downstream face tends to be hotter near the left embankment.

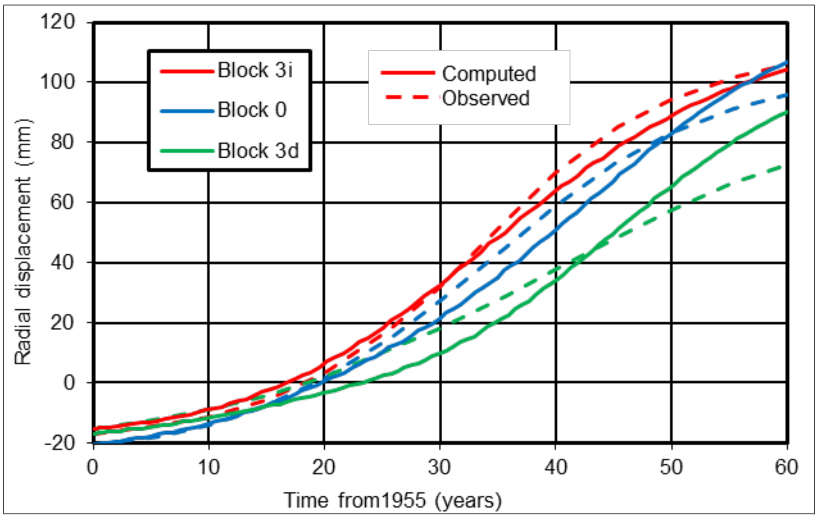


Figure 10: Observed and computed radial displacements

Figure 11: General view of the double curvature arch dam

The parameters of the expansion model were fitted to match the displacement trend at one location. The analyses were conducted with the mesh shown in Figure 12b, which uses about 30,000 elements (second order hexahedrons and first order tetrahedrons). The expansion parameters obtained were:

- swelling at infinite time: 0.001
- latency time: 20,000 days
- characteristic time: 5,000 days

Based on the calibrated parameters, the model was then used to reproduce the complete history of the dam and thus generate the expected displacement histories at other locations. Figure 14 presents comparisons with recorded histories at points at the top of the dam. Since the history at point no. 4 had been used for calibration, a good match could be expected there; but the excellent agreement obtained at the other locations, in spite of the asymmetries displayed by the dam, can only arise because the expansion model represents well the physics of the problem and the parameters are well calibrated. Although not shown here for reasons of space, similarly good agreements are produced when comparing the displacements at intermediate elevations in the dam.

The model was also used to determine the extent of the chemical reaction and the mean expansion at different times, as well as for predicting cracking patterns which are consistent with observations up to the present date.

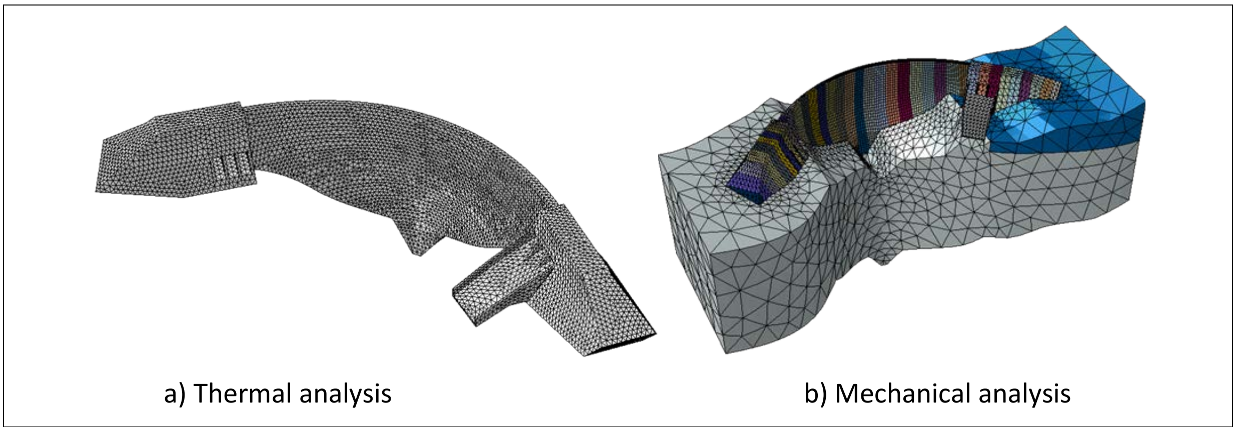


Figure 12: Finite element meshes

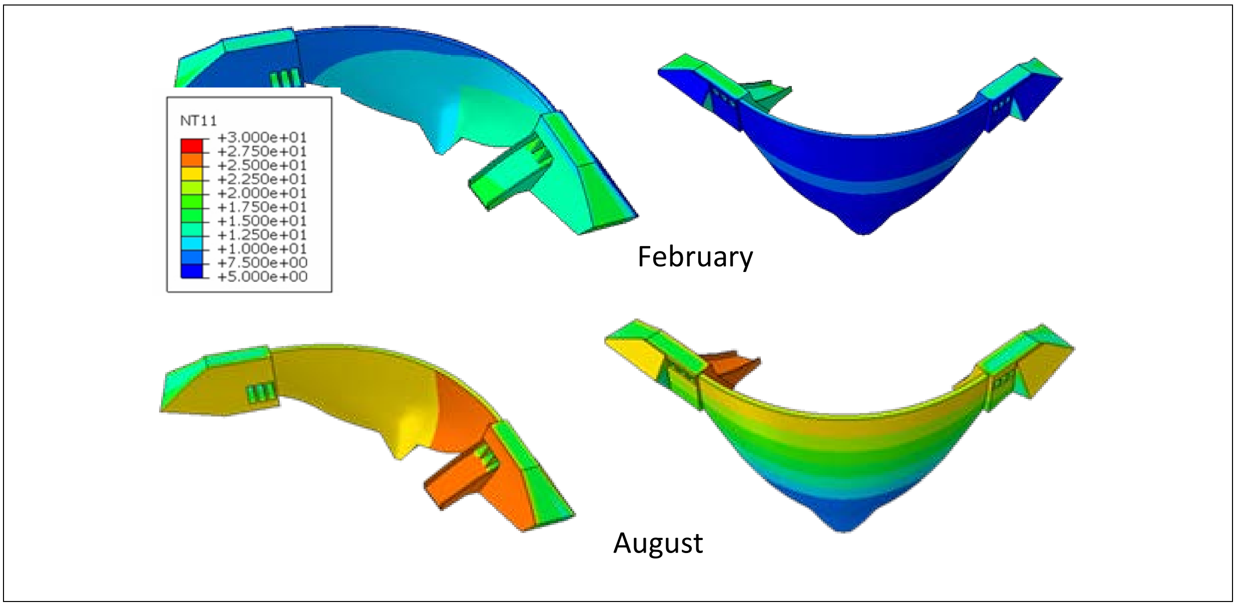


Figure 13: Distribution of temperatures

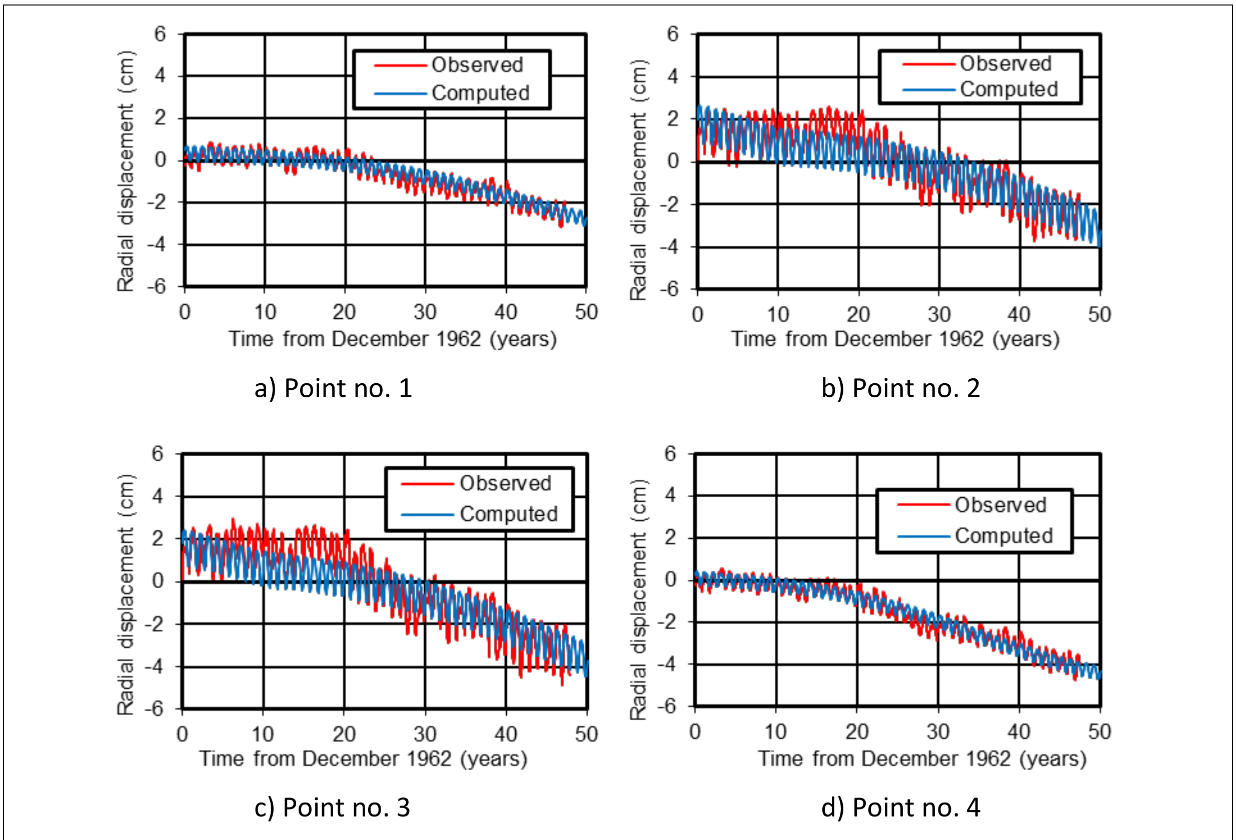


Figure 14: Comparison of recorded and computed displacements

6. Conclusions

Following a review of the state-of-the-art in relation with long term, chemical swelling of concrete and its effects on existing dams, a swelling model was adopted and a subroutine was programmed to implement it in Abaqus/Standard. The newly generated tool and procedures were used to investigate the current situation and to predict the future evolution of a gravity-arch dam and a double-curvature arch dam, both of which were known to be affected by this problem.

The conclusions reached as a result of the work performed are summarily presented below:

a) The swelling model that appears to be more realistic is that initially proposed by Ulm et al [1], but incorporating the later modifications by Saouma and Perotti [3].

b) The model has been programmed in a user subroutine which has been extensively validated to ensure that it performs its intended function.

c) Reasonable agreement has been achieved when trying to reproduce the displacement data available of a large gravity-arch dam undergoing concrete swelling. However the model is not fully successful in reproducing observed asymmetries in the behaviour of the dam. This may be partly due to the scarcity of data on concrete temperatures, a parameter that has a strong influence on the swelling process; but there are also strong suspicions that the concrete is not as homogeneous as assumed.

d) Excellent agreement was observed when modelling a double-curvature arch dam, suffering from a similar swelling pathology. The evolution of displacements at a single point was used to calibrate the parameters of the swelling model, which subsequently provided excellent predictions of the displacements at all other locations of the dam, in spite of the large asymmetries and other differences. It is thought that key to this success, apart from the correctness of the theoretical model, is the availability of detailed temperature data in the body of the dam.

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